

AD-A137 853

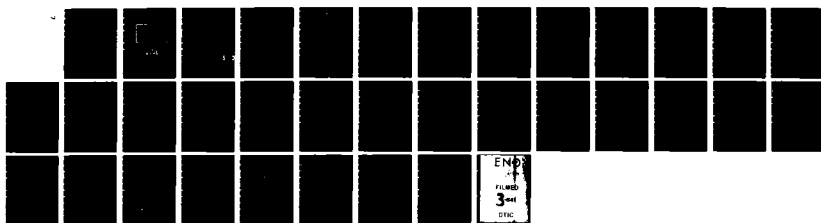
UNSTEADY TURBULENT BOUNDARY LAYERS(U) IOWA INST OF
HYDRAULIC RESEARCH IOWA CITY B R RAMAPRIAN 01 DEC 83
11HR-TC-3 ARO-15780.7-EG DAAG29-79-G-0017

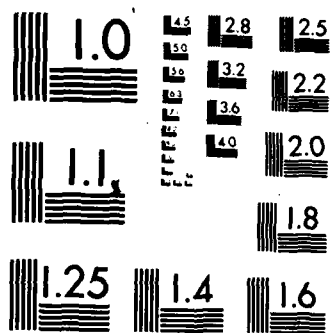
1/1

UNCLASSIFIED

F/G 20/4

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

2

AD A137853

Unsteady Turbulent Boundary Layers

Final Technical Report

by

B.R. Ramaprian

December 1, 1983

U.S. Army Research Office
Grant DAAG29-79-G-0017

IIHR T.C. No. 3



DTIC FILE COPY

Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa

DTIC
ELECTE
S FEB 15 1984
D

84 02 14 139

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution unlimited

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
AI	

Unsteady Turbulent Boundary Layers

Final Technical Report

by

B.R. Ramaprian

December 1, 1983

U.S. Army Research Office
Grant DAAG29-79-G-0017

IIHR T.C. No. 3

DTIC
ELECTE
FEB 15 1984
S D D

Approved for Public Release; Distribution Unlimited

Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242

Qualified requestors may obtain additional copies from the Defense Technical Information Service.

Conditions of Reproduction

Reproduction, translation, publication, use and disposal in whole or in part by or for the United States Government is permitted.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
	AD-A237 853	
4. TITLE (and Subtitle)	5. TYPE OF REPORT & PERIOD COVERED	
Unsteady Turbulent Boundary Layers	Final Technical 30 Sep 82 Dec. 15, 1978 Nov. 30, 1983	
7. AUTHOR(s)	6. PERFORMING ORG. REPORT NUMBER	
B.R. Ramaprian	IIHR-TC-3	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	8. CONTRACT OR GRANT NUMBER(s)	
Iowa Institute of Hydraulic Research The University of Iowa Iowa City, Iowa 52242	DAAG29-79-G-0017	
11. CONTROLLING OFFICE NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	12. REPORT DATE	
	Dec. 1, 1983	
	13. NUMBER OF PAGES	
	27	
	15. SECURITY CLASS. (of this report)	
	Unclassified	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report)		
Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
NA		
18. SUPPLEMENTARY NOTES		
The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
Unsteady Flows Turbulent boundary layers Periodic boundary layers Periodic pipe flows		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)		
A comprehensive study of periodic turbulent boundary layers and pipe flows has been completed. The study has resulted in the identification of the various operating regimes of these flows and the appropriate parameters to characterize them. Comprehensive experimental data on the mean and turbulent properties of these flows, obtained using laser doppler anemometry, have been archived on magnetic tape.		

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES.....	iii
I. INTRODUCTION.....	1
II. FUNDAMENTAL STUDIES OF PERIODIC TURBULENT PIPE FLOW.....	2
II.1. Experimental Studies.....	2
II.2. Numerical Study.....	3
II.3. Summary of the Results.....	3
III. STUDY OF PERIODIC TURBULENT BOUNDARY LAYER.....	5
III.1. The Unsteady Flow Water Tunnel.....	5
III.2. Instrumentation and Data Acquisition.....	6
III.3. Experiments on Steady Boundary Layers.....	7
III.4. Unsteady Flow Experiments.....	7
III.5. Theoretical Analysis of Unsteady Boundary Layers...	10
III.6. Analysis of the Technique of Wall-Shear Stress Measurement with a Heat Flux Gage.....	11
III.7. Numerical Calculations of Unsteady Laminar and Turbulent Boundary Layers.....	12
IV. CONCLUDING REMARKS.....	13
V. REFERENCES.....	14
APPENDIX I.....	26
A.1. Publications under the Sponsorship of this Grant.....	26
A.2. Scientific Personnel who Participated in this Project.....	27

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Classification of periodic turbulent pipeflow. 0, present experiments.....	15
2. Turbulence structure in periodic pipeflow. (a) prediction, (b) experiment. Note that $a_p = \langle uv \rangle / \langle u^2 \rangle \propto \langle uv \rangle / \langle q^2 \rangle$. θ_p and θ_{um} are the phase angles measured with respect to the pressure gradient and U_m respectively.....	16
3. Lay-out of the water tunnel.....	17
4. Distributions of U and \overline{uv} in the periodic turbulent boundary layer. (a) U at $f = 0.5$ Hz, (b) U at $f = 2$ Hz. Symbol station: #, 1; x, 2; +, 3; *, 4; 0, 5, —, Quasi-steady; ---, steady flow at large Reynolds numbers [from Klebanoff (1954)].....	18
5. Distribution of \overline{uv} in the periodic boundary layer. *, 0.5 Hz ($\omega = 10.5$); 0, 2 Hz ($\omega = 42.1$), —, steady flow at mean Reynolds number; ---, Klebanoff (1954).....	19
6. Ensemble averaged velocity and turbulent shear stress in the periodic turbulent boundary layer. *, 0.5 Hz; 0, 2 Hz. Note the results for the two frequency are off-set vertically in each case. The symbol [] represents amplitude.....	20
7. Oscillatory component $\langle v_t \rangle$ of the eddy viscosity in the periodic boundary layer. *, 0.5 Hz; 0, 2 Hz. The vertical line in (b) denotes the extent of unsteady viscous layer. Note the off-set in the vertical coordinate for the two frequencies.....	21
8. Amplitude and phase of the wall shear stress. Shaded area denotes quasi-steady results. L is a reference length scale defined as $2\theta/\bar{c}_f$. Different symbols denote data obtained from different experiments.....	21
9. In-phase component of the oscillatory velocity U_{11} and turbulent shear stress uv_{11} in the periodic boundary layer at "intermediate" frequencies. Symbols, ω : 4.2; \diamond , 4.9; ∇ , 5.8; Δ , 8.3; \square , 10.5; #, 16.8; x, 19.4; +, 23; *, 33, 0; 42.....	22
10. Calculation of the wall shear stress from the wall heat transfer in unsteady flow. L_e is the effective length of the heated element.....	23

11(a). Amplitude results for Blasius-Mean-Flow.....	24
11(b). Phase results for Blasius-Mean-Flow.....	24
12. Comparison of the predictions of the present numerical method with the periodic boundary layer experiments of Jayaraman, Parikh and Reynolds (1982). A simple mixing length model is used in the calculations. Details in Menendez and Ramaprian (1982).....	25

I. INTRODUCTION

The Project was started in December 1978 with the primary objective of studying unsteady turbulent boundary layers. The construction of a large unsteady-flow water tunnel formed a significant part of the effort in this Project. The Project terminated in October 1982 but the studies are presently continuing under a new ARO contract, since then (DAAG-29-83-K-0004). The reporting of this work was delayed till this time in the interest of completeness. Permission for this has been obtained from ARO. The present report summarizes the accomplishments made during the course of this study. Several Journal articles, conference papers, departmental reports and two Ph.D. theses have resulted from this Project. These are listed at the end of this report. Copies of the manuscripts of the publications have been sent to ARO, in each case, at the time of submission. All the experimental data obtained during this study have been archived on magnetic tape in a format compatible with the data base being compiled for AGARD by Dr. Lawrence Carr at NASA Ames Research Center. Dr. Carr is also the Technical Monitor for this Project.

One of the main objectives of the present project was to construct a flow facility in which oscillatory boundary layers could be studied. The construction of the oscillatory-flow water tunnel was a major task. Because of the size and novelty of this tunnel, it was necessary first to construct and test a small scale model of the tunnel so that design improvements could be made relatively inexpensively. Also, this model apparatus could be used for the development and testing of the instrumentation as well as data acquisition software for the HP 1000 minicomputer at the Institute. The ready availability of the small scale unsteady-flow facility and the instrumentation prompted us to perform some basic experiments on fully developed periodic pipe flow. This study proceeded along with the construction of the water tunnel and indeed turned out to be an extremely fruitful endeavor in its own right.

The research effort performed during the Project period can thus be broadly divided into two categories.

- (i) Study of fully developed periodic turbulent flow in pipes.

- (ii) Study of periodic boundary layer on a flat plate in zero (mean) pressure gradient. These are discussed below.

II. FUNDAMENTAL STUDIES OF PERIODIC TURBULENT PIPE FLOW

II.1. Experimental Studies

Using the small scale periodic flow facility, a comprehensive investigation was made of the fully developed periodic turbulent flow of water in a circular pipe of 5 cm diameter (D). In this investigation, detailed measurements including instantaneous longitudinal velocities, U [(using frequency-shifted Laser Doppler Anemometry (LDA))] and instantaneous wall shear stress τ_w (using a flush mounted hot-film gage) were obtained. Three series of experiments were performed. The first series of experiments included measurements of steady flow at five different Reynolds numbers ($Re = \frac{U_m D}{\nu}$) ranging from 20,000 to 80,000. These experiments were used not only to test the experimental procedures but also as the basis for obtaining information on the quasi-steady flow (i.e., flow at infinitely low oscillation frequency). The quasi-steady behavior was then compared with the results of the second series of experiments, in which the flow was oscillated sinusoidally around a mean Reynolds number of 50,000. Two oscillating frequencies (f), namely 0.5 Hz and 3.6 Hz were studied. The higher frequency was of the order of the estimated mean bursting frequency in the flow. The lower frequency can be considered to be an inter-mediate frequency at which the flow still deviated significantly from quasi-steady behavior. In both experiments the amplitude of modulation γ_U was large enough (15% at 3.6 Hz and 64% at 0.5 Hz) to yield new and significant results. From the measurements made, detailed information on various aspects such as velocity, turbulence intensity, Reynolds shear stress, energy spectrum and ensemble averaged energy budget were obtained.

In addition to the detailed experiments mentioned above, a third series of less detailed experiments were performed to understand the amplitude and phase characteristics of the flow. In these experiments, the oscillation frequency was varied from 0.5 Hz to 3 Hz, keeping the modulation amplitude nearly constant at about 25%.

II.2. Numerical Study

Along with the above experimental studies, a numerical study of unsteady pipe flow was also performed. The objective of this study was to examine the implications and limitations of using a successful steady flow turbulence model for predicting periodic pipe flow at high frequencies of oscillation. A time-dependent 'one-equation'-type finite difference calculation procedure was developed for the solution of fully developed unsteady turbulent pipe flow. A Prandtl-energy type turbulence closure model was used in the form identical to that used by previous investigators for the prediction of steady pipe flow. The study yielded very useful results.

The work on periodic pipe flow resulted in a Ph.D. thesis and several journal articles and conference presentations. It is described in complete detail in the report, Ramaprian and Tu (1982).

II.3. Summary of the Results

The pipeflow experiments revealed some departures from the trends suggested by the earlier experiments on unsteady turbulent boundary layers. For example, the Iowa experiments have indicated that the time-mean velocity profile is indeed affected by unsteadiness and so also is the time-mean wall shear stress at oscillation frequencies of the order of the burst frequency. Secondly, wall shear stress measurements showed that its phase lead is of the order of only 10 degrees even at frequencies as high as the bursting frequency, unlike laminar periodic flows in which the phase lead at the corresponding frequency would be nearly 45 degrees. In fact, in the periodic turbulent flow the diffusion effects spread several order of magnitudes farther from the ~~wall~~ than in laminar periodic flow at the same Stokes parameter, $\Omega = \sqrt{\frac{\omega D^2}{\nu}}$, where $\omega = 2\pi f$. This parameter is, therefore, not a relevant parameter for characterizing the periodic turbulent shear flow. Instead, a more relevant parameter is $\omega D / \bar{u}_*$ (where \bar{u}_* is the mean friction velocity) which represents the ratio of the pipe diameter to the turbulent diffusion thickness. Based on this approach, one can classify periodic turbulent shear flows into five regimes: Quasi-steady, low frequency, intermediate frequency, high frequency and rapid oscillation. Figure 1 shows this

classification. Studies on periodic pipeflow by Mizushima and co-workers (1975) have shown that the interaction between the turbulent structure and the imposed oscillation can begin to appear at frequencies an order of magnitude lower than the so-called "mean burst frequency" in the flow. Figure 1 shows three lines, one corresponding to the mean bursting frequency $\bar{\omega}_b$ and the others to the lower (ω_{bL}) and upper (ω_{bU}) limits of the burst frequency histogram. These lines have been obtained from the pipe flow data of Mizushima et al and may not possibly be accurate for boundary-layer flows. Nevertheless, they are adequate for a qualitative categorization of periodic turbulent boundary layers also. The fourth line in Fig. 1 corresponds to the limit at which the flow departs from quasi-steady behavior by a prescribed amount (say the instantaneous velocity profile differs by 5% from the quasi-steady velocity profile).

The behavior of the periodic flow in the various regimes is discussed in detail in Ramaprian and Tu (1982). It will only be mentioned here that regimes III and IV, namely the intermediate and high frequency regimes are the most important from the point of view of application. In fact, many of the recent experiments have been shown (in the above report) to fall under these categories. In particular, the two pipe flow experiments performed at Iowa exemplify the intermediate and high frequency regimes. The effect of imposed oscillations on the turbulence structure increases as the oscillation frequency increases from ω_{bL} towards ω_{bU} . On the other hand, the extent of this effect across the shear layer decreases from 100% of D (or δ) at $f = \omega_{bL}$ to about 10% of D (or δ) at $f = \bar{\omega}_b$ and to about 1% of D (or δ) at $f = \omega_{bU}$. However, it is still true that over a large part of these two regimes, both the intensity and extent of interaction can be significant. But, in order for the magnitude of the interaction to be very significant, it is also essential that the amplitude of modulation should be large (say greater than 30%).

Lastly, the study has shown that the use of steady flow turbulence closure models in a quasi-steady manner for the prediction of periodic flows is not always satisfactory. This is true for the prediction of even the time-mean flow at high frequencies and large amplitude and for the prediction of

other details of the flow even at intermediate frequencies of oscillation. It appears that at intermediate and high frequencies of oscillation, the mean flow, the turbulent kinetic energy ($\langle q^2 \rangle / 2$) and the Reynolds shear stress ($\langle uv \rangle$) are out of phase with one another. Thus, eddy-viscosity type models relating the turbulent transport either to the local mean flow or turbulent structure at any instant--either of the 'gradient' or 'bulk' type cannot describe such flows. Figure 2(a) shows typical behavior of the ensemble averaged eddy viscosity $\langle \nu_t \rangle$ and structure parameter $\langle uv \rangle / \langle q^2 \rangle$ as implied by a typical quasi-steady model of the form: $\langle uv \rangle \propto [\langle q^2 \rangle^{1/2} \lambda]$ (with λ being a prescribed length scale), when used for the prediction of a hypothetical periodic pipe flow at high oscillation frequency and amplitude. Actual experimental results are shown in Fig. 2(b). It is seen that the model implies that both these quantities are 'frozen' at a mean value during the whole cycle at the high frequency (Strouhal No. $S_t = \omega D / 2U_m = 0.07$) while the measurements at 3.6 Hz ($S_t = 0.1$) show large variations in these quantities during the cycle.

III. STUDY OF PERIODIC TURBULENT BOUNDARY LAYER

III.1. The Unsteady-Flow Water Tunnel

The advantages of using a water tunnel instead of a wind tunnel for the study of unsteady turbulent shear flows have been discussed in detail in the literature and will not be repeated here. The present water tunnel is designed such that the free stream velocity at the test section can be varied in a prescribed manner with time. Figure 3 shows the layout of the tunnel.

The tunnel is located on the first floor of the Institute. Water from the main constant head tank on the third floor flows down through a diffuser section into the settling chamber of 1.3 m x 1.3 m cross-section. The settling chamber is provided with a 15-cm-thick layer of honeycomb of 9 mm cell size. The flow is then accelerated through a 9:1 contraction into the test section 2.4 m long and 50 cm x 22.5 cm in cross section. The water finally exits through a pair of rectangular longitudinal slots (2.5 cm x 50 cm) in the cylindrical end piece of 38 cm diameter. The water is guided by a pair of 90-degree turning vanes, into the laboratory sump located below the first floor.

The modulation in the test section velocity is produced by a profiled sleeve rotating over the slotted cylinder. The sleeve profile is designed so as to produce the desired wave form of velocity variation in the tunnel. The sleeve is driven by a 3 HP geared D.C. motor, whose speed is regulated electronically. The sleeve drive assembly is mounted on a carriage, which can slide on longitudinal guides and can be clamped in any desired position so as to obtain the required mean velocity at the test section.

The test section is provided with tempered glass side walls of 18 mm thickness and a 38 mm thick lucite top for flow visualization. A smooth brass plate 50 cm wide and 2.4 m long forms the bottom wall of the test section and is used as the test surface for the boundary layer studies. It is provided with fixtures for the insertion of pressure and wall shear stress instrumentation at various longitudinal locations. A flexible false wall is provided along the top of the test section. The flow area along the test section can be slightly varied by adjusting the profile of this false wall with screws provided for this purpose. One can thus maintain a time-mean zero pressure gradient along the test section. The tunnel is built of 6 mm thick mild steel and strengthened with 62 mm x 12.5 mm ribs. All the steel surfaces are galvanized for protection against rust.

III.2. Instrumentation and Data Acquisition

A two-component LDA system has been used for the measurement of the longitudinal (U) and normal (V) velocity components in the boundary layer over the test surface. This consists of a 15 mw He-Ne laser, an acousto-optic frequency shift device, and two channels of frequency tracker electronics. This system operates in a 3-beam forward-scatter mode with polarization used to separate the channels. A three-dimensional traverse carries the entire LDA optics. The working surface is instrumented with flush mounted hot-film gage for skin-friction measurements. A new technique for the calibration and use of this gage was developed.

A phase averaging technique has been used for the processing of the instantaneous velocity and wall shear stress data. The data are sampled 100 times during a cycle and ensemble averaged over 1000 cycles in the 2-Hz

experiments and 250 cycles in the 0.5 Hz-experiments. This is done using the HP 1000 minicomputer system at the Institute. From these data one can recover the time-mean ($\bar{\phi}$), the deterministic ($\langle \phi \rangle$) and the random (ϕ') components from the instantaneous value of a flow property ϕ .

III.3. Experiments on Steady Boundary Layers

These experiments were carried out to document the quality of the flow, prove the instrumentation and to obtain the data against which the unsteady boundary layer data could be compared. Boundary layer measurements at five longitudinal stations were obtained at several steady freestream velocities. These measurements were made using the two-component LDA and were processed to obtain mean and turbulent flow properties in the boundary layer. Also, spanwise and longitudinal surveys of the test section were made to document flow uniformity, two-dimensionality and the longitudinal pressure gradient in the test section. These tests showed that the flow was uniform to within 0.6% in the region beyond the boundary layers on the walls. There was no detectable organized structure in the spanwise direction. The boundary layer measurements showed that a fully turbulent boundary layer comparable to that of Klebanoff (1954) is obtained in the test section.

III.4. Unsteady Flow Experiments.

The tunnel was set for a freestream velocity variation given by

$$U_e = \bar{U}_e [1 + \gamma_{U_e} \cos 2\pi f t]$$

with $\bar{U}_e = 90$ cm/sec, and $\gamma_{U_e} = 0.4$. Two frequencies, namely $f = 2$ Hz and $f = 0.5$ Hz have been studied. These conditions are comparable to those in the experiments of Jayaraman, Parikh and Reynolds (1982) at Stanford. The higher oscillation frequency studied is comparable to the expected turbulent bursting frequency of about 4 Hz in the boundary layer. Preliminary surveys showed that \bar{U}_e varied by less than 5% along the entire test section length and less than 2% in the range $0.9 < x < 2.1$ meters. The amplitude γ_{U_e} was also found to remain constant within the same limits. Even this small^e (acceptable and

documented) variation is believed to be due to the slight flexibility in the false wall and is likely to be further reduced in the future experiments. The freestream velocity modulation was sinusoidal everywhere along the test section with less than 1% total harmonic distortion as confirmed by a Fourier analysis of the velocity signal. Detailed traverses of the boundary layer were made at several spanwise locations at $x = 2.03$ m from the leading edge of the wall to document the extent of two-dimensionality of the periodic boundary layer. After these initial experiments, boundary layer traverses were made at 5 longitudinal locations at the (nearly) central plane $z = 18.9$ cm. The location, reduced frequency, mean boundary layer thickness $\bar{\delta}$ and time-mean Reynolds number $R_{\theta} = U_e \theta / \nu$ at these stations, for $f = 2$ Hz, are given below (θ is the momentum deficit thickness of the boundary layer).

Station	1	2	3	4	5
x cm	48	69	90	142	203
$\omega x / U_e$	6.7	9.63	12.57	19.83	28.34
$\bar{\delta}$ cm	1.45	1.73	2.09	3.31	3.97
R_{θ}	898	1220	1810	2890	3500

At each location, overlapping traverses were made (usually three times) in order to have redundancy as well as a large density of data points in the profiles. Usually 55-60 points have been used in the presentation of the results. Measurements could be made with confidence down to about 1 mm from the wall ($y^+ \approx 40$) though data have been obtained in some cases at smaller distances from the wall.

From the instantaneous velocity measurements, the quantities, $\langle U \rangle$, $\langle V \rangle$, $\langle u^2 \rangle$, $\langle v^2 \rangle$, $\langle uv \rangle$, $\langle u^3 \rangle$, $\langle u^2 v \rangle$, and $\langle v^3 \rangle$ were obtained as functions of phase position $\theta = 2\pi ft$ in the cycle (θ measured with respect to $\langle U_e \rangle$). The ensemble averaged data were further processed in several ways (such as harmonic analysis to obtain phase and amplitude information of all significant harmonic components, fitting with log and wake distributions to obtain $\langle \theta \rangle$, $\langle \delta \rangle$, etc.). All the raw data and processed data at several levels have been stored on magnetic tape. Wall shear stress $\langle \tau_w \rangle$ (and hence $\langle u_* \rangle$) was

measured at five longitudinal locations using a flush mounted heat flux-type hot-film gage (T1237, made by Thermosystems Inc., Minneapolis). The gage was calibrated in situ in steady flow and used immediately in the unsteady flow. Corrections were applied for calibration drift due to temperature and other effects. Upto 5000 cycles were used in this case for ensemble averaging. Again, measurements were repeated several times on different days with different probe-operating conditions to obtain redundancy in the data. All the data have been stored on tape. The performance of the heat-flux gage as a skin-friction gage was analyzed in detail (see Section III.6).

The results are presented and discussed in detail in Menendez and Ramaprian (1983) which also forms the Ph.D. thesis of Menendez. Some of the important experimental results are summarized below.

(i) Spatial history effects on the time-mean properties have been identified and interpreted for a periodic turbulent boundary layer developing in zero time-mean pressure gradient. It has been found that the oscillation accelerates the development of the outer flow, while it has little effect on the inner flow. The modification of the outer flow can be interpreted as a shift in the virtual origin of the turbulent boundary layer. For large Reynolds numbers, the time-mean properties tend to approach their steady distributions at the time-mean free-stream velocity. The small residual differences between the two can be considered to be 'frequency effects'. See Figs. 4(a) and 4(b).

(ii) Frequency effects on the time-mean turbulence properties have also been identified and correlated. They produce a small positive departure in the outer layer, relative to the steady flow distribution at the same Reynolds number, for $8 \lesssim \tilde{\omega} \lesssim 20$ where $\tilde{\omega} = \frac{\omega \Delta}{u_* (\theta/\Delta - U)}$ being a characteristic thickness of the boundary layer defined as $\Delta = \int_0^{\infty} \frac{U}{U_e U_*} dy$. Typical results are shown in Fig. 5 for $\tilde{\omega} = 10.5$ and $\tilde{\omega} = 42.1$.

(iii) The behavior of the oscillatory components of the motion has been seen to confirm what was previously known. In particular, many of the conclusions of Ramaprian and Tu (1982) on periodic pipe flows apply equally well to unsteady boundary layers. The thickness of the unsteady layer, i.e. the layer over which unsteady viscous effects are significant, [see Fig. 6]

has been characterized by the quantity u_*/ω , in agreement with Ramaprian and Tu (1982). Phase differences of up to 360 degrees in the oscillatory components of the turbulence properties, across the unsteady layer, have been measured. Eddy-viscosity results obtained from the measurements, and shown in Figs. 7(a), (b), indicate that neither a quasi-steady (zero phase-shift) nor a 'frozen' (zero amplitude) turbulence model is appropriate for unsteady boundary layers at the present frequencies.

(iv) Wall-shear-stress measurements have been made using a flush-mounted heat-flux gage. The time-mean wall shear stress has been found to decrease slightly with frequency, a trend opposite to that observed in pipe flow [Ramaprian and Tu (1982)]. The amplitude of oscillation of the skin friction coefficient C_f , denoted by $[<C_f>]$ in Fig. 8(a), is close to the quasi-steady value at all the frequencies. Larger phase leads (of over 30 degrees) than those reported by Ramaprian and Tu (1982) have been observed in the boundary layer at the higher frequencies [Fig. 8(b)].

III.5. Theoretical Analysis of Unsteady Boundary Layers

An asymptotic theory, for large Reynolds numbers $R_* = \bar{u}_* \bar{\Delta} / \nu$, has been developed for the oscillatory motion. This theory does not employ any specific turbulence model. It is valid for both boundary layers at zero and adverse time-mean pressure gradients and fully developed pipe and channel flow, and has been successfully applied to the present and previous available experimental information. The theory identified the frequency parameters $\tilde{\omega} = \omega \bar{\Delta} / u_*$ and $\alpha = \bar{u}_*^2 / \omega \nu$, as the appropriate parameters to characterize the oscillatory motion at large Reynolds numbers. The first one is analogous to that introduced by Ramaprian and Tu (1982) based on eddy viscosity arguments.

Based on the values of these parameters, four frequency regimes have been identified (excluding the quasi-steady regime):

- * Low frequency regime: $\tilde{\omega} \lesssim 1$ or $(\alpha \gtrsim R_*)$
- * Intermediate frequency regime: $1 \ll \tilde{\omega} \lesssim R_*^{1/2}$ or $(R_*^{1/2} \lesssim \alpha \ll R_*)$
- * High frequency regime: $R_*^{1/2} \ll \tilde{\omega} \ll R_*$ or $(1 \ll \alpha \ll R_*^{1/2})$

* Very high frequency regime: $\tilde{\omega} \geq R_*$ or $(\alpha \leq 1)$

Similarity laws have been identified for each one of these frequency regimes. These laws are the extension to unsteady flows of the well known "law-of-the-wall", "velocity-defect law" and "logarithmic law" for steady flows and are discussed in detail in Menendez and Ramaprian (1983). The agreement of this theory with experiments is demonstrated by the typical results shown in Figs. 9(a) and 9(b) for the in-phase components of the velocity and Reynolds shear stress in the unsteady layer ($\hat{y} = \frac{2\pi f y}{\bar{u}_*} \sim 1$) at intermediate frequencies of oscillation.

III.6. Analysis of the Technique of Wall-Shear-Stress Measurement with a Heat Flux Gage

The performance of a flush mounted heat flux gage as a device for the measurement of skin friction in unsteady boundary layers was analyzed. Two important aspects were considered in this problem:

- (i) the relationship between surface heat transfer and skin friction in periodic flow at various frequencies and amplitudes of oscillation and
- (ii) the heat transfer to the substrate of the hot film.

The problem was originally discussed in some detail by Bellhouse and Schultz (1966). They solved the laminar thermal boundary-layer problem over the film by neglecting the effect of pressure gradient and unsteadiness to obtain the following well known relationship

$$\tau_w^{1/3} \propto Q_w \quad (1)$$

or equivalently

$$\tau_w^{1/3} = AE^2 + B \quad (2)$$

where τ_w is the wall shear stress, Q_w is the heat transfer rate at the wall and E is the voltage output by the anemometer driving the hot film. A and B are constants of calibration. Their analysis was improved in the present study by including the pressure gradient and unsteady terms in the analysis. The resulting relationship is described by

$$\tau_w = (AE^2+B)^3 + \frac{c_1}{(AE^2+B)} \frac{dU_e}{dt} + c_2 A \frac{dE^2}{dt} \quad (3)$$

where the constants c_1 and c_2 depend on the fluid properties and the effective dimensions of the heated film. The relationship between $\langle \tau_w \rangle$ and $\langle Q_w \rangle$ obtained from this improved analysis was compared with the 'exact' results obtained from a numerical solution of unsteady hydrodynamic and thermal boundary layers as well as with the results obtained from the conventional analysis represented by eq. (2). A typical set of results is shown in Fig. 9 for conditions roughly appropriate to the use of the Probe T1237 in water at 20°C. Note that at very low oscillation frequency [Fig. 10(a)], there is negligible error in using eq. (2). Figure 10(b) corresponds roughly to the measurement of $\langle C_f \rangle$ in the present boundary layer studies. It is seen that the present analysis results in a significant improvement in the estimation of $\langle C_f \rangle$. Figure 10(c) corresponds to the use of the probe for turbulence measurements. It is again seen that the present analysis brings the estimated $\langle C_f \rangle$ closer to the 'exact' value. In general, it was found that the heat flux gage can be used satisfactorily in most of the proposed studies though an error of about 7 degrees in the estimation of the phase angle of $\langle \tau_w \rangle$ is possible in extreme cases. The details of this study are described in Menendez and Ramaprian (1984).

III.7. Numerical Calculations of Unsteady Laminar and Turbulent Boundary Layers

A finite difference method was developed for the prediction of unsteady turbulent boundary layers in arbitrary pressure gradients. While similar methods have been developed by a few others, the feature that distinguishes the present effort from the others is that the accuracy of the present method has been tested in a very systematic and rigorous manner. This was done by using the procedure to predict periodic laminar boundary layers in zero and adverse pressure gradients. The results were compared with classical solutions for the asymptotic limits of low and high frequency oscillation as well as with the more recent higher order analytical solutions for a less restrictive range of oscillation frequencies. The results were also compared

with experimental results on periodic laminar boundary layers. Further, in this method, the finite difference calculations are carried up to the wall. Hence, the method, when used for turbulent flow calculations, does not involve the use of the so called 'wall functions'. The calculations are performed in the physical (x-y) coordinate system but the domain of calculation is allowed to expand with the growth of the boundary layer. Variable grid spacing is used to optimize accuracy and computational time. An implicit scheme is used for the time integration. The finite difference scheme is set up such that flow reversals near the wall (occurring under conditions of high frequency and large amplitude) can be satisfactorily handled. In fact, one of the important merits of this method is that it retains the numerical accuracy even at very large oscillation frequencies $[(\omega x/U_e) \approx 20]$ and predicts the asymptotic shear-wave solution. This is seen from the typical results shown in Figs. 11(a) and 11(b) for a periodic laminar boundary layer with Blasius-mean flow. The performance of this method, when used for periodic turbulent flows is seen from the typical results shown in Figs. 12(a) and (b). In this case, the calculations have been made for one of the experimental conditions of Jayaraman, Parikh and Reynolds (1982). A simple turbulence model, namely the Prandtl-mixing length model was used. The details of this work have been reported in Menendez and Ramaprian (1982). More advanced turbulence models have also been tried.

IV. CONCLUDING REMARKS

In summary, it can be stated that the present study has produced significant contributions to the understanding of periodic turbulent shear flows. A comprehensive set of data on periodic pipe flows and boundary layers in (time-mean) zero pressure gradient are now available for use by the research community. The asymptotic analysis of unsteady turbulent shear flows has led to a categorization of these flows and the establishment of general similarity laws for the different regions of the flow. Apart from these, the water tunnel constructed under this program is a major facility at Iowa, which will be used in the future for a variety of studies on steady and unsteady turbulent flows. Further studies on unsteady boundary layers in adverse pressure gradient are currently being pursued under a new contract from ARO.

V. REFERENCES

1. Bellhouse, B.J., Schultz, D.L. (1966), "Determination of Mean and Dynamic Skin Friction, Separation and Transition in Low-Speed Flow with a Thin-Film Heated Element", J. Fluid Mech., Vol. 24, pp. 379-400.
2. Hill, P.G. and Stenning, A.H. (1960), "Laminar Boundary Layers in Oscillatory Flow", J. of Basic Engineering, Vol. 82, pp. 593-608.
3. Jarayaman, R., Parikh, P., Reynolds, W.C. (1982), "An Experimental Study of the Dynamics of an Unsteady Turbulent Boundary Layer", Technical Report TF-18, Dept. of Mech. Eng., Stanford University.
4. Klebanoff, P.S. (1954), "Characteristics of Turbulence in a Boundary Layer with Zero Pressure Gradient", NACA TN 3178.
5. Menendez, A.N. and Ramaprian, B.R. (1983), "Study of Unsteady Turbulent Boundary Layers", IIHR Report No. 270, University of Iowa, Iowa City.
6. Menendez, A.N. and Ramaprian, B.R. (1984), "The Use of the Flush-Mounted Hot-Film Gage for Skin-Friction Measurement in Unsteady Turbulent Flows", IIHR Report under preparation.
7. Mizushima, T., Maruyama, T., Hirasawa, H. (1975), "Structure of the Turbulence in Pulsating Pipe Flows", J. of Chem. Eng. of Japan, Vol. 8, No. 3, pp. 210-216.
8. Ramaprian, B.R. and Tu, S.W. (1982), "Study of Periodic Turbulent Pipe Flow", IIHR Report No. 238, University of Iowa, Iowa City.

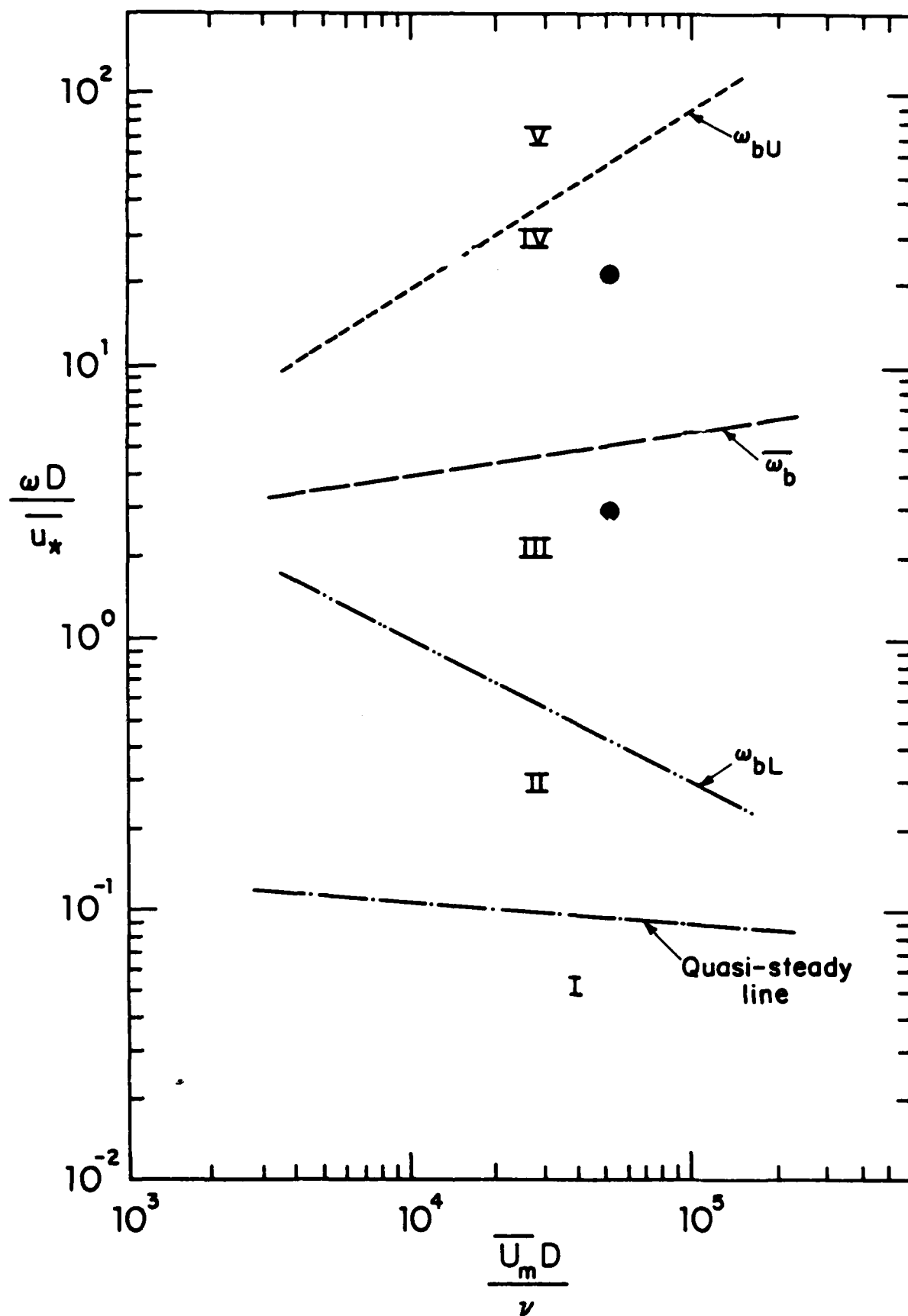


Figure 1. Classification of periodic turbulent pipeflow. 0, present experiments

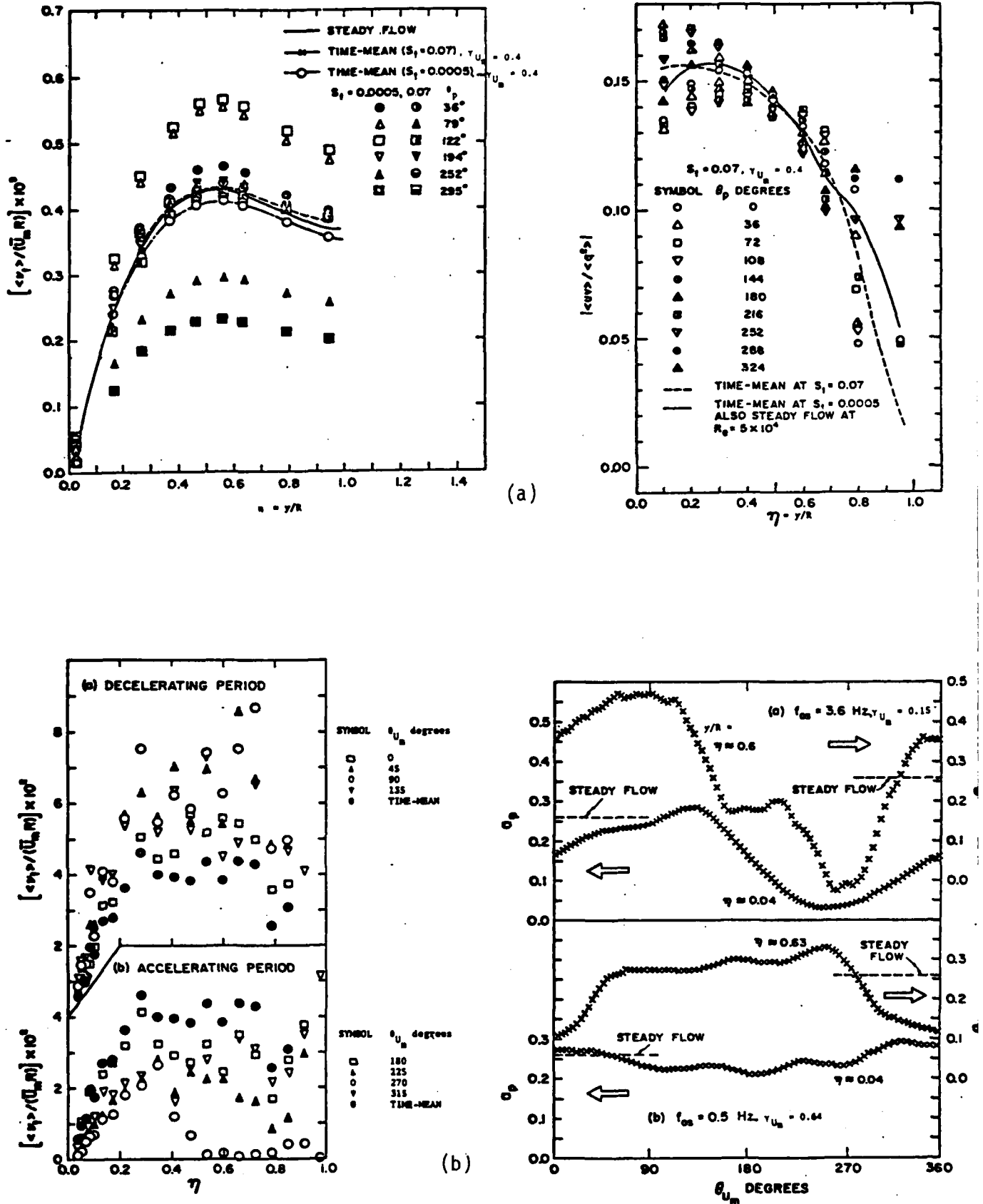


Figure 2. Turbulence structure in periodic pipeflow. (a) prediction, (b) experiment. Note that $a_p = \langle uv \rangle / \langle u^2 \rangle \approx \langle uv \rangle / \langle q^2 \rangle$. θ_p and θ_{U_m} are the phase angles measured with respect to the pressure gradient and U_m respectively

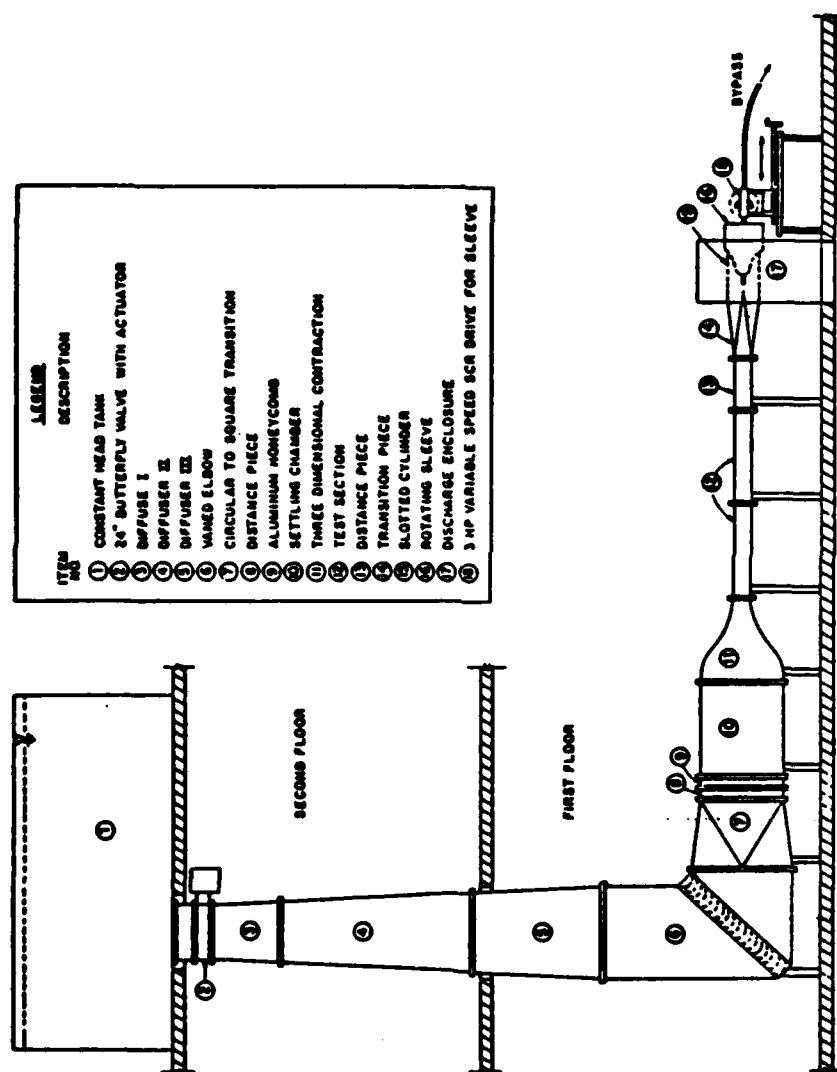


Figure 3. Lay-out of the water tunnel

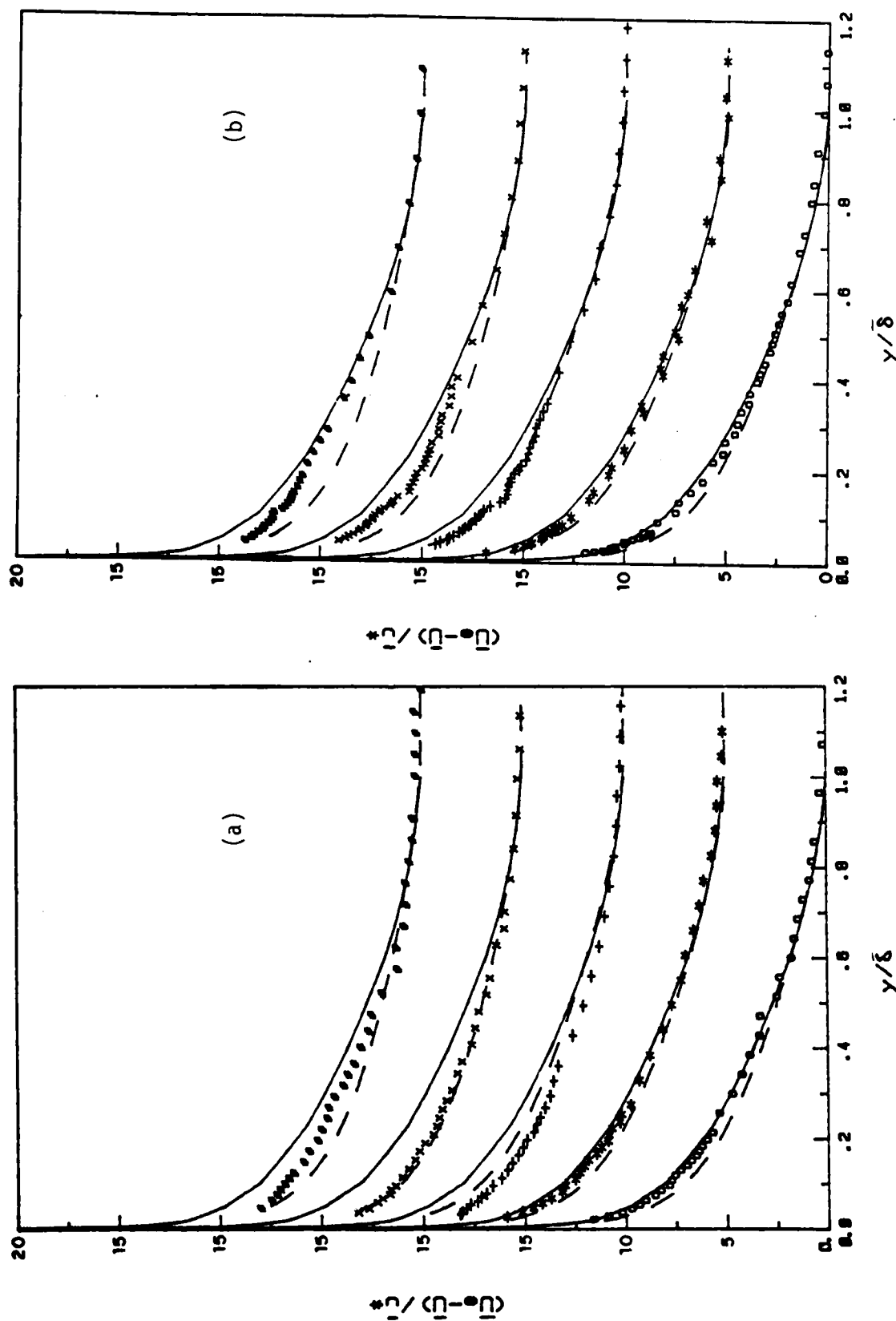


Figure 4. Distributions of U and uv in the periodic turbulent boundary layer. (a) U at $f = 0.5$ Hz, (b) U at $f = 2$ Hz. Symbol station: #, 1; x, 2; +, 3; *, 4; 0, 5, ---, Quasi-steady; ---, steady flow at large Reynolds numbers [from Klebanoff (1954)]

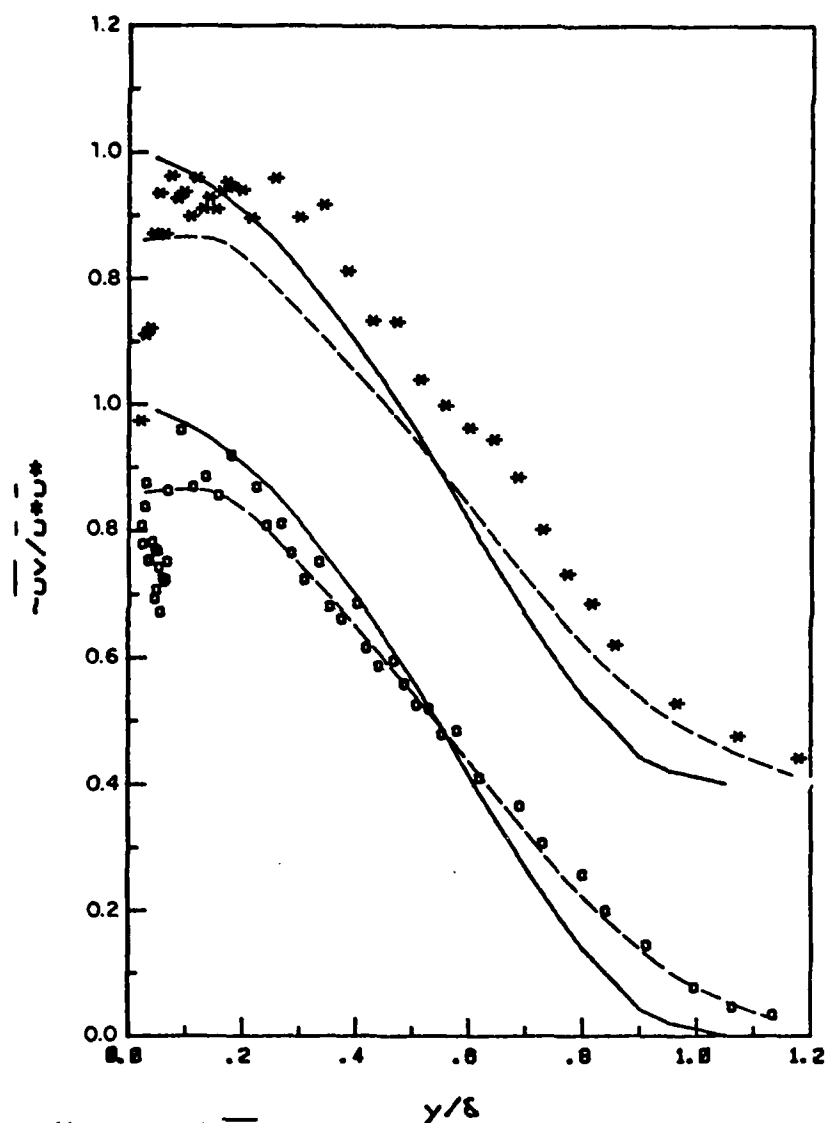


Figure 5. Distribution of \overline{uv} in the periodic boundary layer. *, 0.5 Hz ($\tilde{\omega} = 10.5$); o, 2Hz ($\tilde{\omega} = 42.1$), —, steady flow at mean Reynolds number; ---, Klebannof (1954)

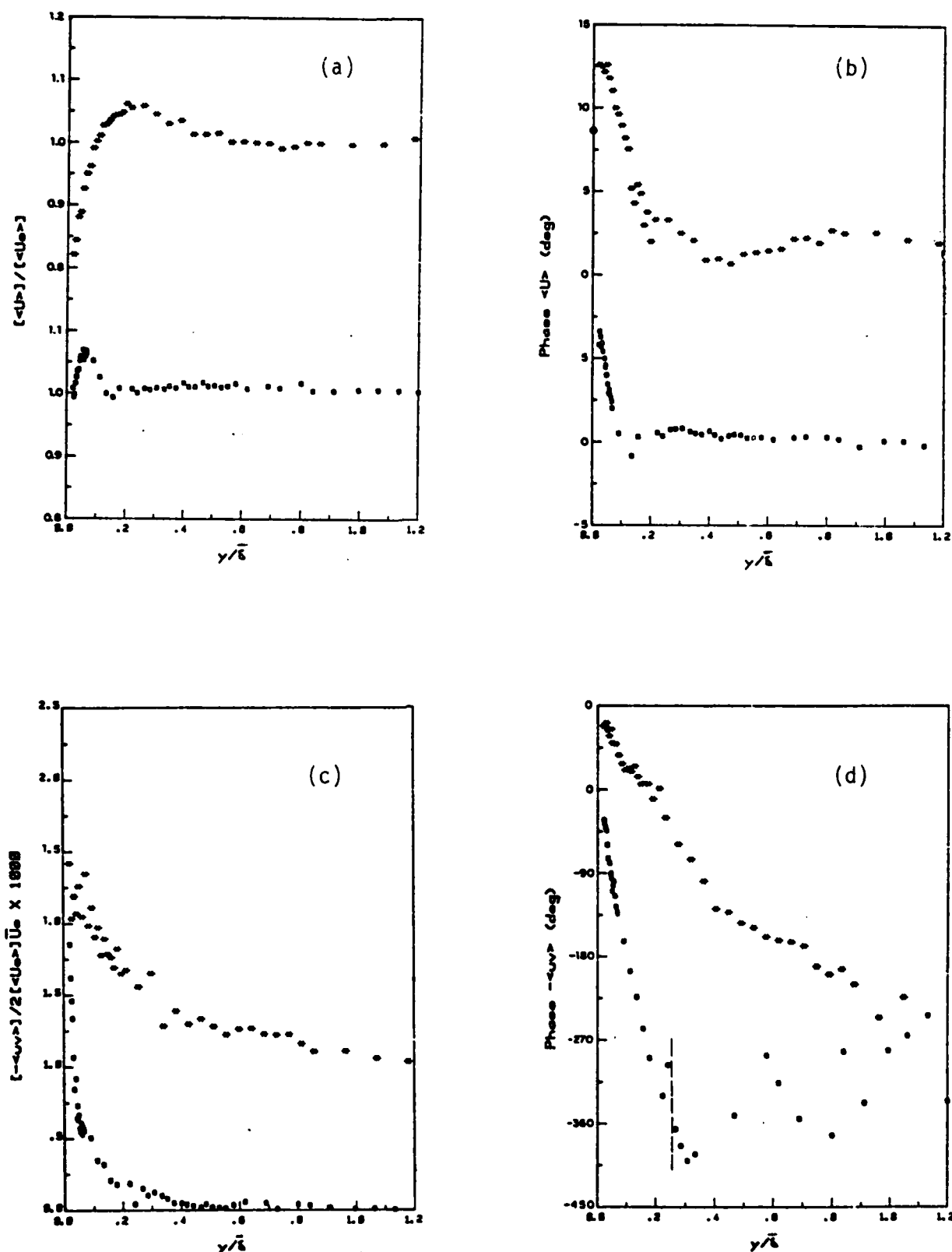


Figure 6. Ensemble averaged velocity and turbulent shear stress in the periodic turbulent boundary layer. *, 0.5 Hz; O, 2 Hz. Note the results for the two frequency are off-set vertically in each case. The symbol [] represents amplitude

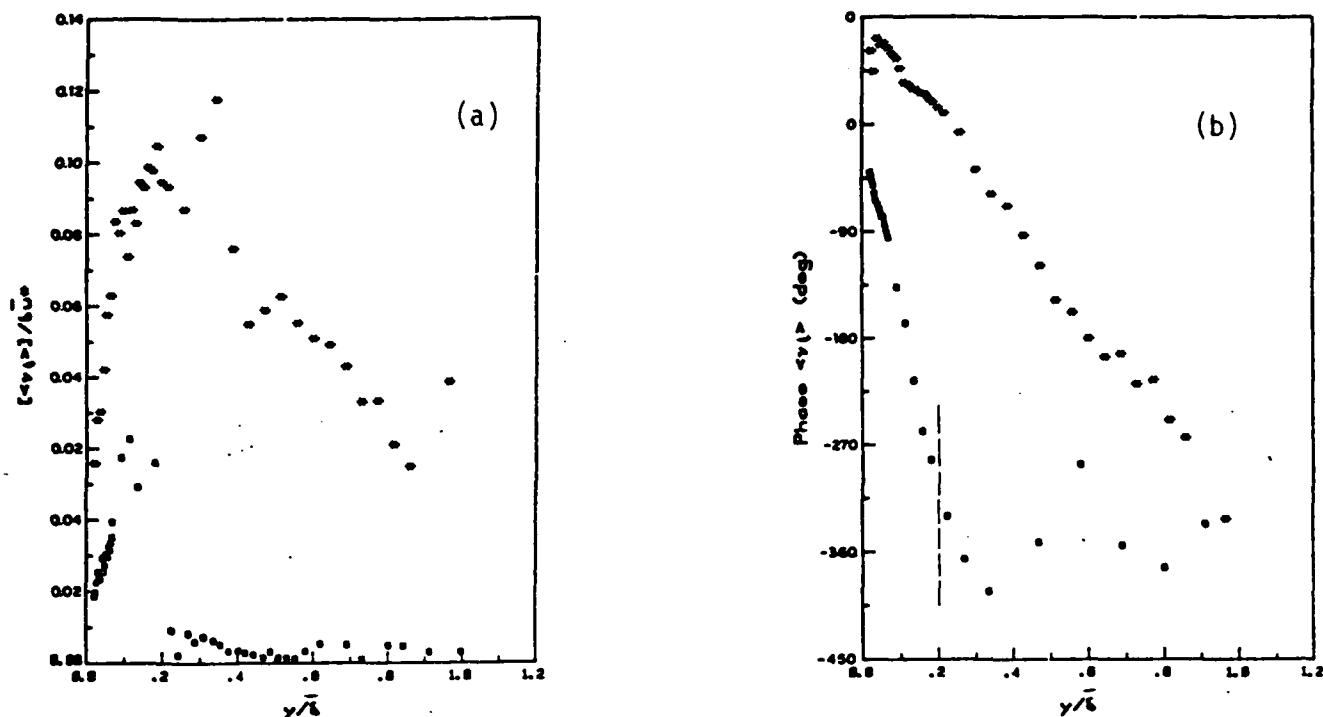


Figure 7. Oscillatory component $\langle v_y' \rangle$ of the eddy viscosity in the periodic boundary layer. *, 0.5 Hz; O, 2 Hz. The vertical line in (b) denotes the extent of unsteady viscous layer. Note the off-set in the vertical coordinate for the two frequencies

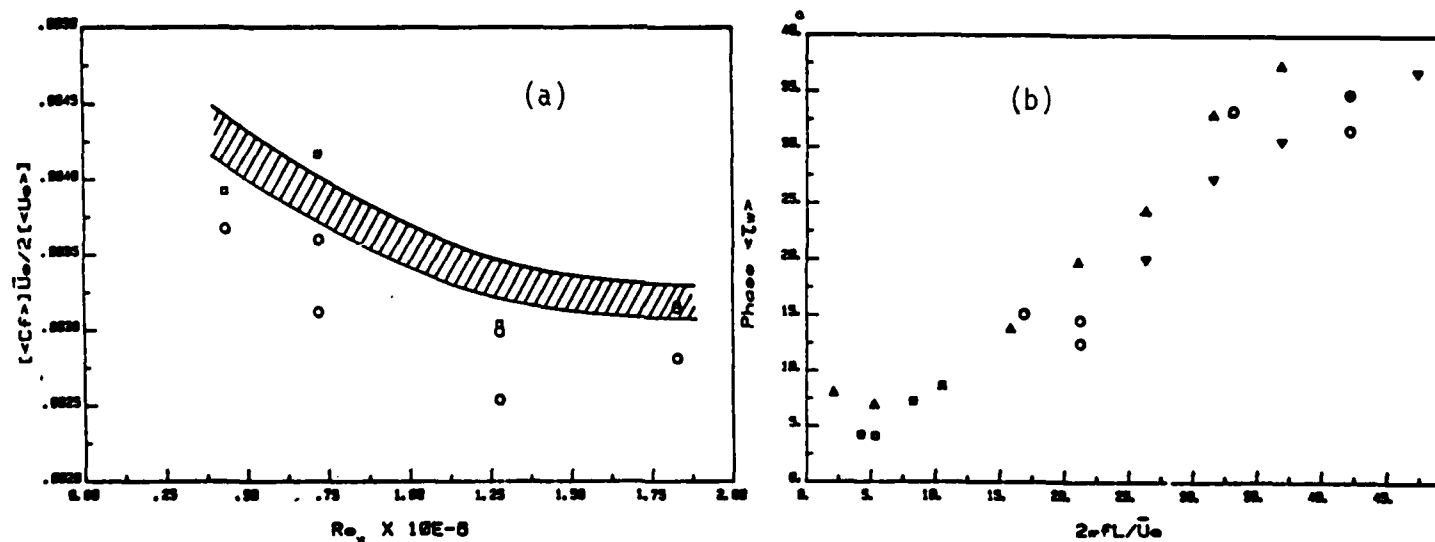


Figure 8. Amplitude and phase of the wall shear stress. Shaded area denotes quasi-steady results. L is a reference length scale defined as $2\theta/\bar{C}_f$. Different symbols denote data obtained from different experiments

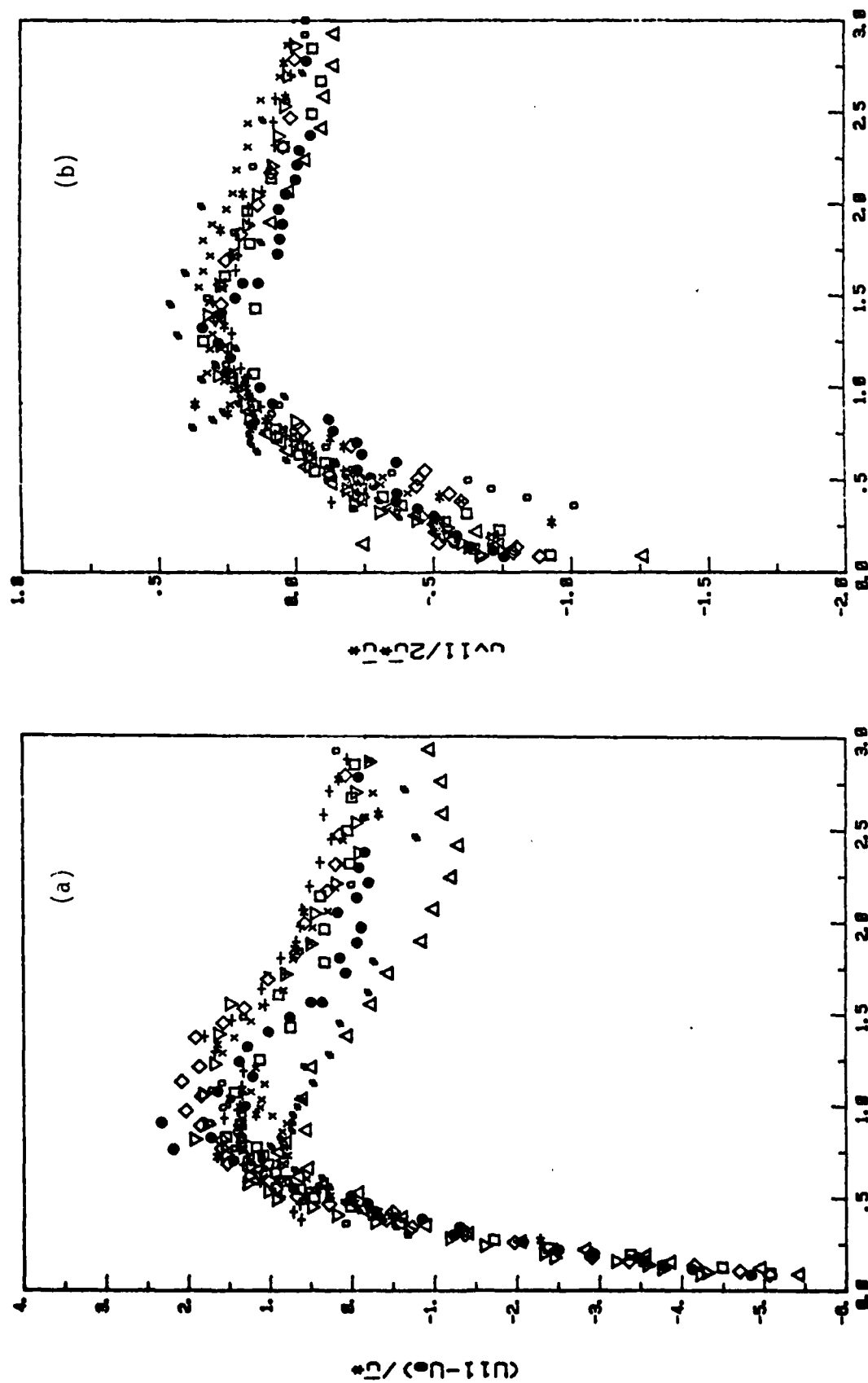


Figure 9. In-phase component of the oscillatory velocity u_{11} and turbulent shear stress uv_{11} in the periodic boundary layer at "intermediate" frequencies.
 Symbols, ω : \diamond , 4.2; ∇ , 4.9; Δ , 5.8; \square , 8.3; \circ , 10.5; \times , 16.8; $+$, 19.4; $*$, 23; \cdot , 33; \circ , 42

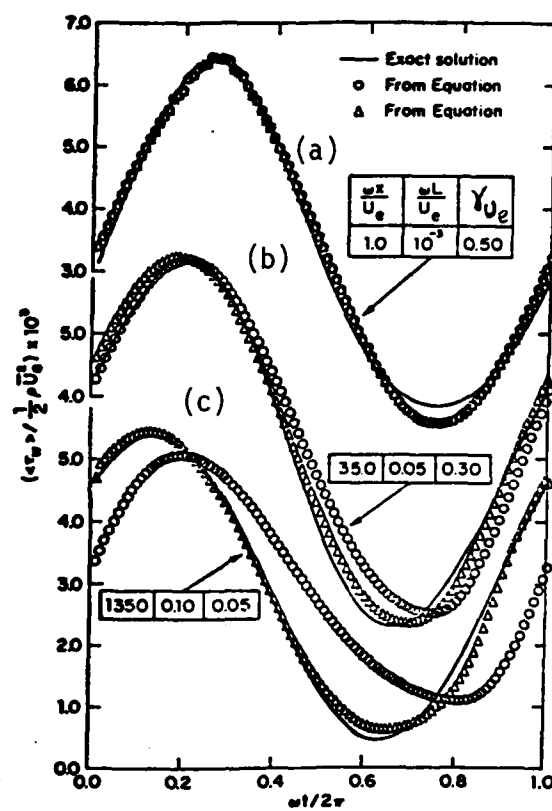


Figure 10. Calculation of the wall shear stress from the wall heat transfer in unsteady flow. L_e is the effective length of the heated element

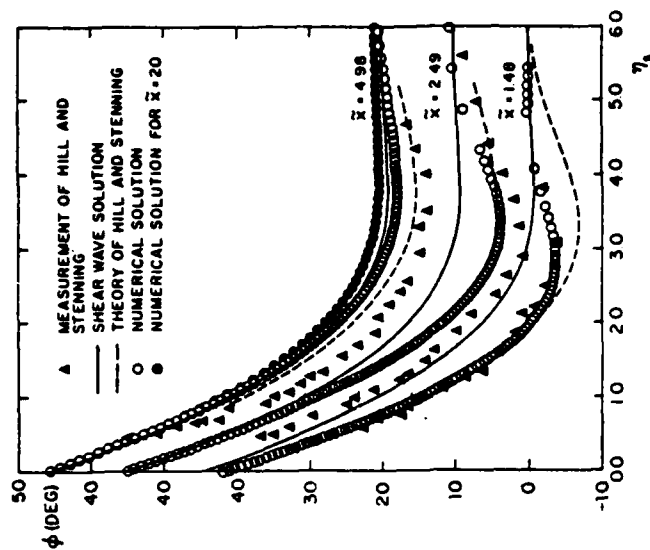


Figure 11(a). Amplitude results for Blasius-Mean-Flow

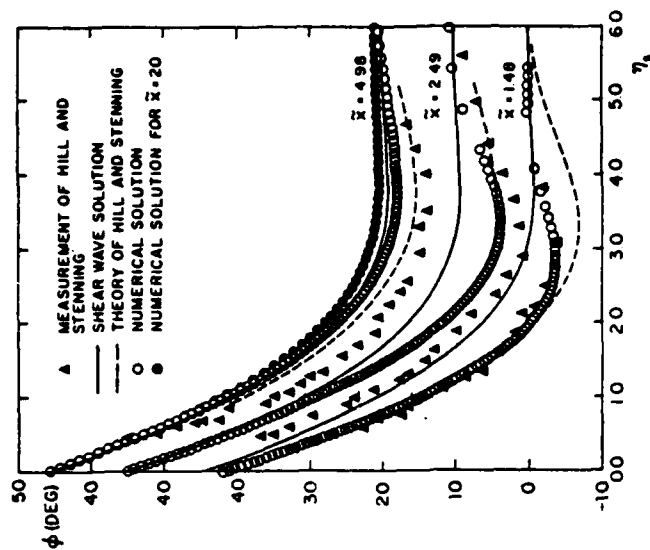


Figure 11(b). Phase results for Blasius-Mean-Flow

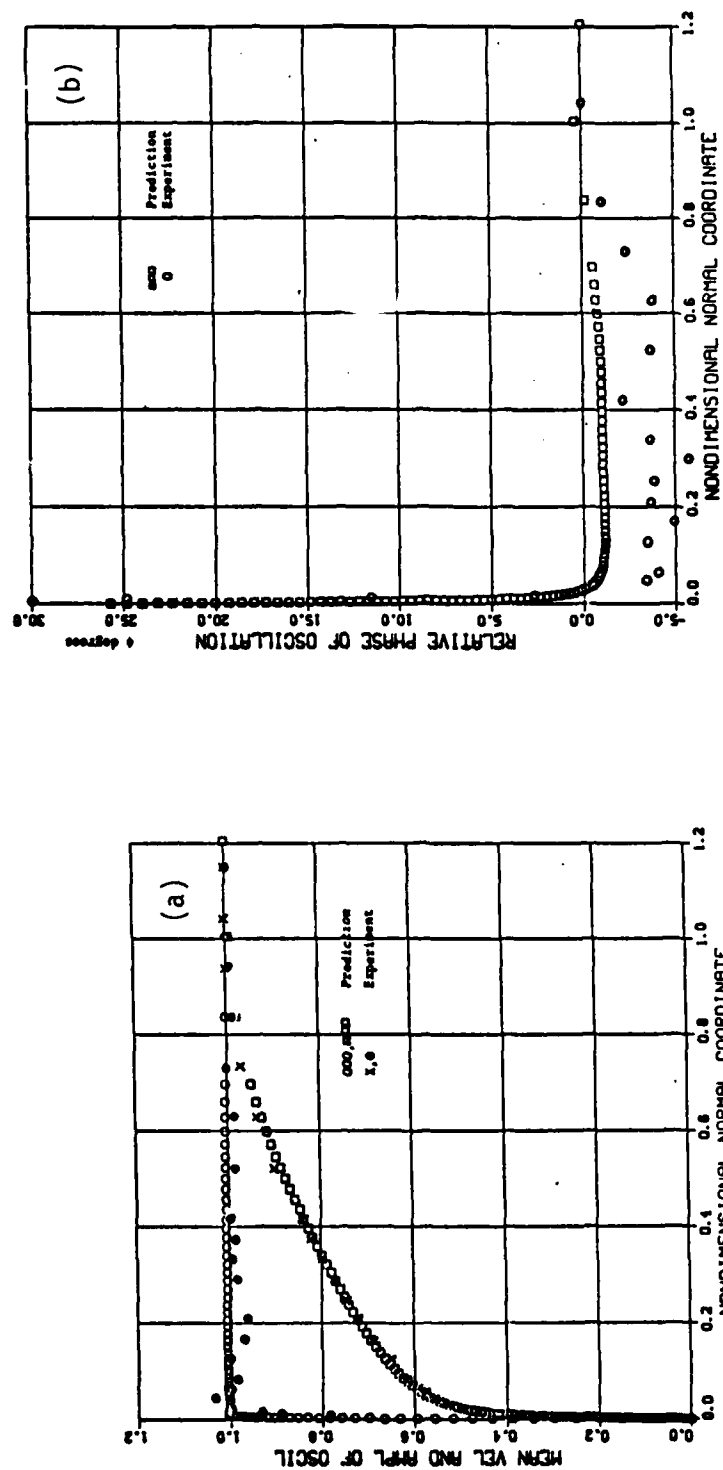


Figure 12. Comparison of the predictions of the present numerical method with the periodic boundary layer experiments of Jayaraman, Parikh and Reynolds (1982). A simple mixing length model is used in the calculations. Details in Menendez and Ramaprian (1982)

APPENDIX I

A.1. Publications under the Sponsorship of this Grant

(a) Theses

1. S.W. Tu (1982) "Study of Periodic Turbulent Pipe Flow" (Ph.D.).
2. Menendez, A.N. (1983) "Study of Unsteady Turbulent Boundary Layers" (Ph.D.)

(b) Journal Articles

1. Ramaprian, B.R. and Tu, S.W., "An Experimental Study of Oscillatory Pipe Flow at Transitional Reynolds Numbers", J. of Fluid Mechanics, Vol. 100, Pt. 3, 1980, pp. 513-544.
2. Ramaprian, B.R. and Tu, S.W., "Calibration of a Heat Flux Gage for Skin Friction Measurement", To appear in the J. of Fluids Engineering.
3. Tu, S.W. and Ramaprian, B.R., "Quasi-Steady Modeling of Periodic Turbulent Pipe Flows", accepted by AIAA Journal.
4. Tu, S.W. and Ramaprian, B.R., "Fully Developed Periodic Turbulent Pipe Flow, Part I. Main Experimental Data and Predictions", J. of Fluid Mechanics, Vol. 137, 1983, pp. 31-58.
5. Ramaprian, B.R. and Tu, S.W., "Fully Developed Periodic Turbulent Pipe Flow, Part II. The Detailed Structure of the Flow", J. of Fluid Mechanics, Vol. 137, 1983, pp. 59-81.
6. Menendez, A.N. and Ramaprian, B.R., "Prediction of Periodic Boundary Layers", accepted by the Int. J. for Numerical Methods.

(c) Conference Papers

1. Ramaprian, B.R. and Tu, S.W., "Periodic Turbulent Pipe Flow at High Frequencies of Oscillation", Unsteady Shear Flows, eds. R. Michel, J. Cousteix and R. Houdeville, Springer-Verlag, West Berlin, 1981, pp. 47-57.
2. Ramaprian, B.R. and Tu, S.W., "Periodic Turbulent Boundary Layer", paper presented at the Joint ASME/ASCE Conference, Boulder, Colorado, June 1981.
3. Menendez, A.N. and Ramaprian, B.R., "Calculation of Unsteady Boundary Layers", Proceedings of the Third International Conference on Numerical Methods in Laminar and Turbulent Flow, University of Washington, Seattle, August 8-11, 1983, pp.

4. Ramaprian, B.R., Tu, S.W. and Menendez, A.N., "Periodic Turbulent Shear Flows", Proceedings of the 4th Symposium on Turbulent Shear Flows, Karlsruhe, West Germany, September 12-14, 1983, pp. 8.18-8.23.
5. Ramaprian, B.R., "A Review of Experiments in Periodic Turbulent Pipe Flow", Keynote Paper to be presented at the ASME Energy-Sources Technology Conference and Exhibition, New Orleans, February 12-17, 1984.

(d) Departmental Reports

1. Ramaprian, B.R. and Tu, S.W., "Experiments on Transitional Oscillatory Flow", IIHR Report No. 221, 1979, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City.
2. Ramaprian, B.R. and Tu, S.W., "Study of Periodic Turbulent Pipe Flow", IIHR Report No. 238, The University of Iowa, Iowa City, January 1982.
3. Menendez, A.N. and Ramaprian, B.R., "Calculation of Unsteady Boundary Layers", IIHR Report No. 248, Aug. 1982, The University of Iowa, Iowa City, Aug. 1982.
4. Menendez, A.N. and Ramaprian, B.R., "Study of Unsteady Turbulent Boundary Layers", IIHR Report 270, The University of Iowa, Iowa City, Dec. 1983 (being submitted to J. of Fluid Mechanics as a two-part paper).
5. Menendez, A.N., and Ramaprian, B.R., "The Use of the Flush-Mounted Hot-Film Gage for Skin-Friction Measurement in Unsteady Turbulent Flows", IIHR Report, under preparation, (also being submitted to the J. of Fluid Mechanics).

A.2. Scientific Personnel who Participated in this Project

Dr. B.R. Ramaprian	Principal Investigator
Dr. V.C. Patel	Co-Principal Investigator
S.W. Tu	Graduate Research Assistant - received Ph.D. (1982)
A.N. Menendez	Graduate Research Assistant - received Ph.D. (1983)

END

FILMED

3-84

DTIC